Directional Effects in a Daily AVHRR Land Surface Temperature Dataset Over Africa

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***Abstract*—Land surface temperature (LST) is a key indicator of the land surface state and can provide information on surface-atmosphere heat and mass fluxes, vegetation water stress, and soil moisture. Split-window algorithms have been used with National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data to estimate instantaneous LST for nearly 20 years. However, the low accuracy of LST retrievals associated with intractable variability has often hindered its wide use. In this study, we developed a six-year daily (day and night) NOAA-14 AVHRR LST dataset over continental Africa. By combining vegetation structural data available in the literature and a geometric optics model, we estimated the fractions of sunlit and shaded endmembers observed by AVHRR for each pixel of each overpass. Although our simplistic approach requires many assumptions (e.g., only four endmember types per scene), we demonstrate through correlation that some of the AVHRR LST variability can be attributed to angular effects imposed by AVHRR orbit and sensor characteristics, in combination with vegetation structure. These angular effects lead to systematic LST biases, including "hot spot" effects when no shadows are observed. For example, a woodland case showed that LST measurements within the "hot-spot" geometry were about 9 K higher than those at other geometries. We describe the general patterns of these biases as a function of tree cover fraction, season, and satellite drift (time past launch). In general, effects are most pronounced over relatively sparse canopies (tree cover $<60\%$), at wet season sun-view angle geometries (principal plane viewing) and early in the satellite lifetime. These results suggest that noise in LST time series may be strongly reduced for some locations and years, and that long-term LST climate data records should be normalized to a single sun-view geometry, if possible. However, much work remains before these can be accomplished.**

***Index Terms*—Angular effects, Advanced Very High Resolution Radiometer (AVHRR), geometric optics, land surface temperature (LST), vegetation structure.**

I. Introduction

LAND surface temperature (LST), defined as the effective kinetic temperature of the earth surface "skin," is a key climatological variable and contributes to the magnitude and partitioning of energy fluxes at the earth's surface. Knowledge of the LST allows us to infer information about surface heat fluxes, vegetation properties, and soil moisture [1]–[3] and can help in the prediction of vegetation hydric stress and water requirements for crops [4], [5]. Currently, some model parameterizations [6] use air surface temperature to assess the surface state. However, LST is more directly related to surface properties than is the surface-level air temperature [7]. Therefore, improvement in the accuracy of LST retrievals would likely lead to more accurate parameterization of the surface. For example, Kustas and Norman [8] showed that uncertainty in LST of 1 °C to 3 °C could produce errors up to 100 W/m^2 in surface flux estimates.

Remote sensing is the only means available to monitor the temperature of the earth's surface on a synoptic and regular basis. The National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) has measured the brightness temperature, a function of LST, of the earth for more than 20 years. However, orbit and sensor characteristics can impart temporal and spatial artifacts in the AVHRR data that impair their accuracy, especially as long-term time series. For example, the supposedly sun-synchronous orbit of the NOAA afternoon satellites drifts to later equatorial crossing times as the satellite ages. The drift has averaged approximately 30 min per year through their three- to five-year operational life [9]. For NOAA-14, this caused the local solar observation time, at the equator, to drift from 13:30 to later than 16:00. Recently, researchers have attempted to correct these effects [7], [10], [43] in some AVHRR products; however, no drift correction is currently applied to operational AVHRR LST products [e.g., NOAA, National Aeronautics and Space Adminstration (NASA)].

Effects of variability in the observation and illumination angles (i.e., sun-view geometry) on LST retrieval has received less attention. This variability results from two main factors: 1) the angular and local time variation across a single scan and 2) the nine-day periodicity of the AVHRR ground track. With a scan angle of $\pm 55^\circ$ off nadir (equivalent to a 68° view zenith angle on the earth's surface), the swath spans about 2 h in local time of observation at the equator. The time span increases with increasing latitude. The nine-day periodicity of the NOAA platform means that a given observation and illumination geometry associated with a given land target is only repeated each nine days.

For a flat Lambertian surface, the time of observation would be the primary cause of sensor-induced variability in the retrieved radiance. However, for a nonhomogeneous and structured surface, the sun-view geometry determines the relative proportions of the surface endmembers (e.g., sunlit soil, shaded trees) viewed by the sensor. Since endmember temperatures typically differ, the ensemble temperature of the scene can vary with the sun-view geometry.

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In the past 20 years, many theoretical and empirical studies at local scale have addressed angular variability in thermal infrared measurements [11]–[13]. Further, some regional scale studies have exploited the dual-angle observations of the Along Track Scanning Radiometer (ATSR) to retrieve separate soil and vegetation temperatures [14], improve the estimates of surface sensible heat flux [15], and minimize errors in the retrieved sea surface temperature (SST) [16]. Several researchers [17]–[19] have speculated about the possible effects of sun-view geometry for global observations made with wide-field-of-view sensors. However, the effects have not been demonstrated for sensors with moderate spatial resolutions (i.e., ≥ 1 km) such as AVHRR and Earth Observation System (EOS) Moderate Resolution Imaging Spectrometer (MODIS). The testing of this hypothesis can be challenging given the high-frequency changes in LST due to natural changes in meteorology (e.g., air temperature, cloudiness), surface conditions (e.g., soil moisture), and the natural diurnal cycle (solar heating). Indeed, this dynamic behavior is the desired signal from LST observations, and ideally should be significantly greater than observation-induced LST variability. If sun-view effects do exist, the LST data retrieved from AVHRR and MODIS would contain systematic variability imparted from sources independent of the natural land surface kinetic temperature.

In this paper, we describe a new daily NOAA-14 AVHRR LST dataset and interrogate it for evidence of angular variability over continental Africa. Specifically, we characterize systematic effects resulting from the varying observation and illumination geometry of AVHRR measurements in its nine-day periodicity as well as its six-year orbital decay.

In our approach, we assume that the most significant source of angular variability in the observed LST is a function of local vegetation structure and the temperatures of the endmembers, including shadows. To perform such a study at the continental scale, and for multiple years, many assumptions are required. We assume that each observation scene can be characterized by only four isothermal surface components (endmembers), and that directional differences in emissivity are negligible. This simplistic representation of surface temperature allows us to correlate LST to sun-view geometry given the projected fractions for those geometries.

II. Theory

The radiance reaching a thermal infrared (TIR) sensor, at height h, is the sum of two main components: the radiance emitted and reflected by the surface attenuated by the spectral transmittance of the atmosphere, and the upwelling radiance from the atmosphere integrated over the depth of the atmospheric path. The radiance detected by the sensor can be formulated as

$$L(\lambda,\theta,\phi,h) = \left(L(\lambda,\theta,\phi,0)\tau_\lambda(\phi,\theta) + \int_0^h L(\lambda, T_{\mathrm{at}}(z)) \frac{\partial \tau_\lambda(\phi,\theta,z)}{\partial z} dz \right) f(\lambda) \quad (1)$$

where $f(\lambda)$ is the normalized response of the instrument in a finite bandpass, $L(\lambda, T_{\mathrm{at}}(z))$ is the upwelling thermal infrared radiance (assumed isotropic) emitted by the atmosphere at height $z, \tau_\lambda(\phi,\theta,z)$ is the atmospheric transmittance at height $z, \tau_\lambda(\phi,\theta)$ is the total atmospheric transmittance along the path of observation, and $L(\lambda,\theta,\phi,0)$ is the radiance emitted by the surface and observed at zenith angles θ, azimuth angles ϕ, and at wavelength λ, and can be formulated as

$$\begin{aligned} L(\lambda,\theta,\phi,0) &= B_\lambda[T_b(\theta,\phi)] \\ &= \varepsilon_\lambda(\theta,\phi)B_\lambda[T_{\mathrm{sr}}(\theta,\phi)] + [1-\varepsilon_\lambda(\theta,\phi)](E_{\mathrm{at}}/\pi) \end{aligned} \quad (2)$$

where $T_b(\theta,\phi)$ is the surface directional brightness temperature, i.e., the temperature of a black body that has the same radiance as the radiance exiting that surface, $\varepsilon_\lambda(\theta,\phi)$ is the directional emissivity of the surface, and E_{at} is the spectral irradiance at the earth's surface (assuming thermal equilibrium and a Lambertian atmosphere). Assuming knowledge of surface emissivity and irradiance, the directional radiometric temperature of the surface $T_{\mathrm{sr}}(\theta,\phi)$, or apparent temperature of the surface, can be obtained by inverting Planck's function described as

$$B_\lambda[T_{\mathrm{sr}}(\theta,\phi)] = \frac{2hc^2}{\lambda^5\left(e^{hc/k\lambda T_{\mathrm{sr}}(\theta,\phi)}-1\right)} \quad (3)$$

with $B[T_{\mathrm{sr}}(\theta,\phi)]$ in units of watts per square meter per micrometer ($\mathrm{W\cdot m^{-2}\cdot \mu m^{-1}}$), and where h (6.6262E-34 J·s) is the Planck constant, k (1.3806E-23 $\mathrm{J\cdot K^{-1}}$) is the Boltzmann constant, and c (299 792 458 $\mathrm{m\cdot s^{-1}}$) is the speed of light in the vacuum.

VI. Conclusion

The objective of the present study was to develop a daily (day and night) AVHRR LST dataset for the years 1995 to 2000, and to determine if it contained systematic biases as a result of the varying sun-view geometry characteristics of the observing system. Although theoretical and local "point-scale" ground studies show evidence of angular dependency in LST observations, we are not aware of any prior studies that demonstrate that LST data, collected by wide-field-of-view sensors such as AVHRR, are systematically affected by sun-view geometry of the observing system.

Our hypothesis was based on the assumption that the radiance received by the sensor is a weighted average of the radiance emitted from scene endmembers. The weighting factors depend on the projected fraction of each endmember of the sensor. We expected to detect an induced, deterministic component of the LST variability that is mainly a function of the geometry variability of the observation, in addition to the natural variability of the surface temperature. We have demonstrated that there is a bias in the NOAA-14 AVHRR LST dataset that results from the orbit and sensor characteristics. This bias is not uniform in time or in space and responds not only to the latitudinal and seasonal patterns of the AVHRR geometry, but also to the differences in tree cover density. Our results suggest that, given the orbital drift of NOAA-14, the angular effects on LST decrease with time past launch. Although sensors degrade with age, the reduction in sensor-induced biases in afternoon AVHRR LST with time may provide some compensation.

Our results highlight the need to account for this artifact in the AVHRR LST data. A methodology could be developed to normalize the data to a common illumination and observation geometries and, therefore, remove the angular dependency that currently exists in the AVHRR thermal retrievals. This is the subject of current work and will be reported at a later date.